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WORKSHOP ON SPACE PHYSICS:
"Materials in Micorgravity"
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"Turbulent Combustion"

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II. TURBULENT COMBUSTION.

PRACTICAL COMBUSTION DEVICES ARE TRAVERSED BY A TURBULENT FLOW (GENERALLY). IN THIS CASE, ALL THE THERMODYNAMIC PARAMETERS FLUCTUATES IN SPACE AND TIME, SO DOES ALSO THE FLAME PARAMETERS.

IN A TURBULENT FLAME THE FLAME CHARACTERISTICS ARE NO MORE SOLELY DEPENDENT ON THE CHEMICAL COMPOSITION AND THE TEMPERATURE AND PRESSURE BUT ALSO ON THE FLOW PARAMETERS

2.1. EXAMPLES OF PRACTICAL COMBUSTION SYSTEMS

* TURBULENT PREMIXED FLAMES
* TURBULENT DIFFUSION FLAMES

combustors or hazard control systems without close reference to empirical data and previous experience. They are, however, becoming very useful tools in the design process. It is a prime goal of combustion research to advance the capabilities of such mathematical descriptions of combustion systems.

1.2 SOME PRACTICAL COMBUSTION SYSTEMS

1.21 Simple Gas Burners

Many domestic and some industrial gas burners use "port" stabilized flames, being a modification of the traditional bunsen burner. The fuel induces its own air supply by ejector action and the reactants are premixed by the time they reach the burner ports. Combustion problems of interest include:

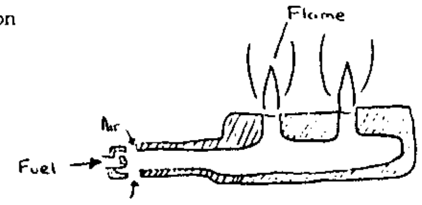
(a) flame speed

(b) flame stabilization (blow-off and flash-back)

(c) flame radiation

(d) noise

(e) pollutant emissions, particularly NO_x.



1.22 Swirl Burners

Many oil and gas fired furnace burners use swirl stabilized flames where the flame is stabilized in the recirculation zone at the centre of the vortex formed by the swirling air which is supplied by a forced draft fan. Combustion problems of interest include:

(a) flame stabilization

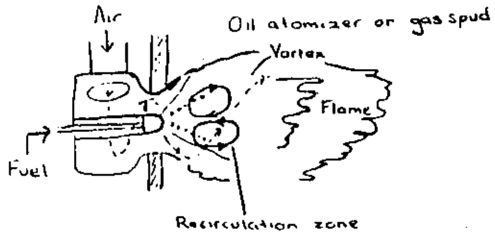
(b) droplet evaporation and burning

(c) fuel air mixing

(d) flame length

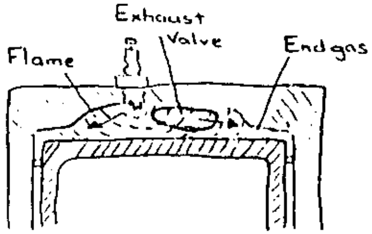
(e) flame radiation

(f) pollutant emissions, particularly NO_x and smoke



1.23 Spark Ignition Engine

In this system a highly turbulent flame progresses through the fuel-air mixture. Further compression of the end gas occurs with tendency to pre-ignition and "knock". Combustion problems include:



(a) temporal and spatial uniformity of fuel-air mixture

(b) uniformity of ignition

(c) turbulent flame speed

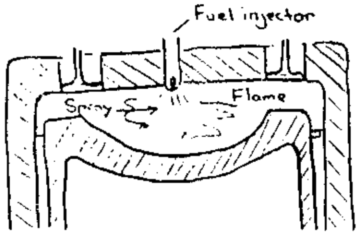
(d) knock

(e) heat transfer

(f) pollutant emissions - particularly CO, HC, NO_x, particulates.

1.24 Diesel Engine

In this engine fuel is sprayed into the high temperature air and auto-ignites. Combustion problems include:



(a) evaporation and autoignition of initial fuel

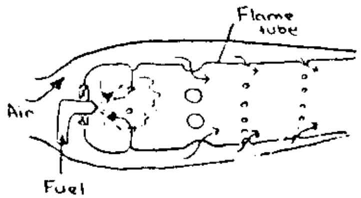
(b) spray combustion and air mixing

(c) complete combustion of all available oxygen

(d) pollutant emissions, particularly smoke and NO_x.

1.25 Gas Turbine

Fuel is sprayed and burnt in about one quarter of the air flow. The remainder is used for dilution of products to final desired turbine inlet temperature. Combustion problems include:



(a) achievement of high combustion intensity

(b) stabilization over wide range of pressure

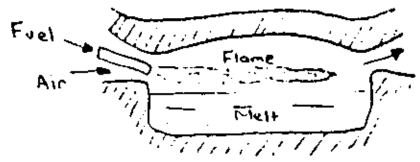
(c) spray combustion

(d) achievement of high turbulence with low pressure drop

(e) pollutant emissions, particularly smoke, NO_x and at idle CO and HC.

1.26 Industrial Furnace

The sketch shows a typical industrial furnace. A long luminous diffusion flame is used to provide proper heating of the melt. Combustion problems include:



(a) Soot formation to provide luminosity

(b) air-fuel mixing

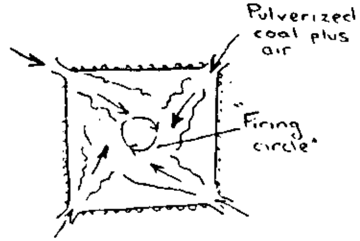
(c) heat transfer, convective and radiative

(d) soot burn-out

(e) pollutant emissions especially particulates, CO.

1.27 Pulverized Coal Furnace

The sketch shows a corner fired P.F. furnace. Pulverized coal is carried into the furnace with a stream of primary air. Secondary air is admitted above and below the coal injection ports. Volatile components in the fuel pyrolyse out close to the ports and flame initiates there. The solid carbon in the fuel burns out in the main volume of the furnace radiating heat to the "water walls". Combustion problems include:



(a) flame stabilization

(b) carbon particle burn out

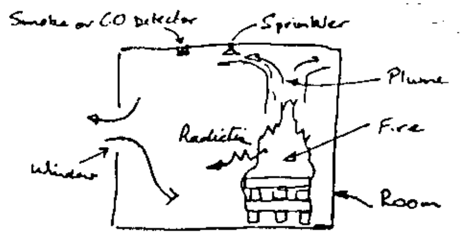
(c) heat transfer

(d) pollutant emissions, particularly ash, soot, NO_x, SO_x

(e) surface fouling.

1.2.8 Fire Control Systems

A fire in a confined space produces a plume of flame, smoke and hot gases which spreads along the ceiling. Radiation from the flame pyrolyses the fuel at the base of the fire and can cause ignition of other objects. Development of the fire is ultimately controlled by the orifice characteristics of the window or other openings. Combustion problems include:



(a) rate of fire growth

(b) fire breakthrough to adjoining rooms

(c) location of smoke detectors

(d) design of sprinkler systems.

2.2. SOME BASIC DEFINITIONS OF TURBULENCE

THE EQUATIONS WHICH DESCRIBE A TURBULENT FLOW ARE AGAIN THE NAVIER-STOKES EQUATIONS, BUT EACH THERMODYNAMIC PARAMETER HAS TWO PARTS.

$$X(t) = \overline{X} + x'(t)$$

INSTANTANEOUS VALUE; MEAN VALUE; FLUCTUATING VALUE

WHERE $\overline{x'(t)} \equiv 0$ BY DEFINITION

THIS GIVES RISE TO UNKNOWN CORRELATIONS SUCH AS IN THE MASS CONSERVATION EQUATION

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0$$

$$\frac{\partial(\rho + \rho')}{\partial t} + \partial\left[\frac{(\rho+\rho')(u+u')}{\partial x}\right] = 0$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho'}{\partial t} + \frac{\partial}{\partial x}\left(\rho u + \rho' u + u'\rho + \rho' u'\right) = 0$$

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho u}}{\partial x} + \frac{\partial \overline{\rho' u'}}{\partial x} = 0$$

$\rho' u' \equiv$ TURBULENT MASS TRANSPORT.

IF WE TAKE THE TURBULENT VELOCITY FIELD, WE HAVE 3 FLUCTUATING VELOCITY

$$u', v', w'$$

IN ISOTROPIC TURBULENCE

$$u' = w' = v'$$

SO THE TURBULENT KINETIC ENERGY

$$q = \frac{3}{2} u'^2$$

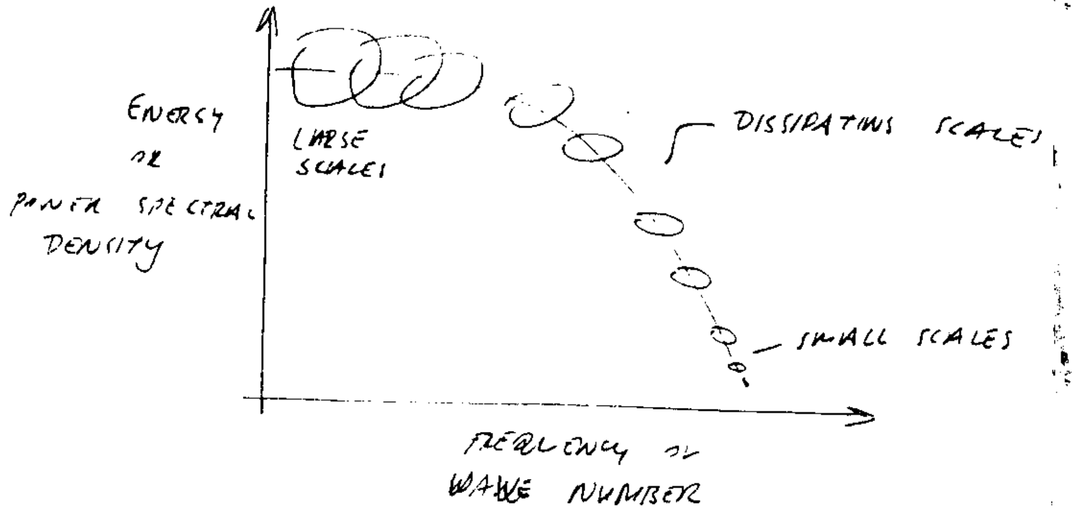
TURBULENCE INTENSITY IS, FOR EXAMPLE

$$\frac{u'}{\overline{u}} \text{ or } \frac{v'}{\overline{u}}$$

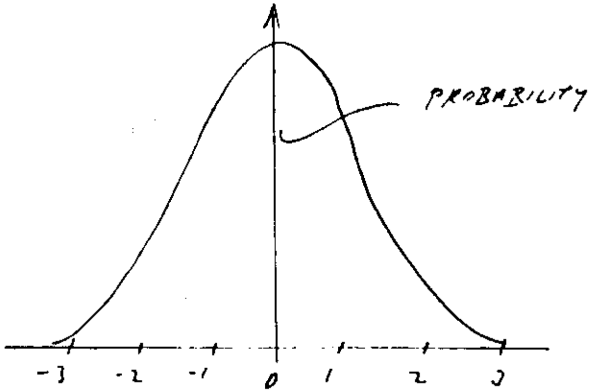
IN A TURBULENT FLAME THE RATIO

$$\frac{u'}{S_L}$$ IS VERY IMPORTANT

TURBULENCE HAS A WIDE SPECTRUM OF TIME AND LENGTH SCALES



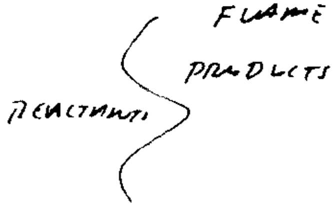
THE PROBABILITY DENSITY FUNCTION (THE HISTOGRAMME) IS ALSO USED IN THE REPRESENTATION OF TURBULENCE



$\sigma = (u-\bar{u})/\sqrt{\overline{u'^2}}$ R.M.S.

IN PREMIXED TURBULENT FLAMES, DEPENDING ON THE INTENSITY AND THE SCALES OF THE TURBULENCE OF THE REACTANTS, SEVERAL REGIMES ARE POSSIBLE

I) $u' < S_L$, $L > \delta_L$ WRINKLED LAMINAR FLAME REGIME

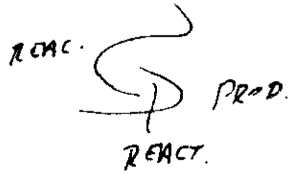


CONTINUOUS FLAME FRONT

II) $u' > S_L$, $L > \delta_L$ CORRUGATED FLAME FRONT

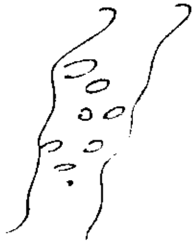
CONTINUOUS FLAME FRONT

IIa) $u' \gg S_L$, $L > \delta_L$ PACKET COMBUSTION REGIME



RUPTURED FLAME FRONT

III) $u' > S_L$, $L < \delta_L$



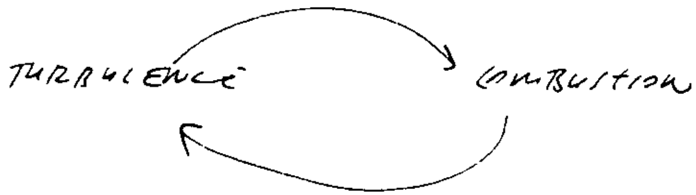
THICKENED FLAME FRONT

IN EACH OF THESE REGIMES THE FLAME ZONE IS THICKER THAN THE LAMINAR ONE, AND THE FLAME PROPAGATION VELOCITY OR THE MEAN REACTION RATE IS HIGHER THAN THE LAMINAR CASE.

THE GENERAL OBJECTIVE OF TURBULENT COMBUSTION RESEARCH IS TO PREDICT THE TURBULENT FLAME PROPERTIES GIVEN THE NATURE OF THE MIXTURE (THE COMPOSITION) AND THE CHARACTERISTICS OF THE INCOMING TURBULENCE.

BUT

TURBULENT COMBUSTION IS A REAL INTERACTION



EXPERIMENTALLY, NON-INTRUSIVE LASER-BASED OPTICAL TECHNIQUES ARE MORE AND MORE USED SUCH AS

- LASER DOPPLER ANEMOMETRY (VELOCITY)
- RAYLEIGH SCATTERING (DENSITY, TEMPERATURE)
- MIE SCATTERING (DENSITY)
- RAMAN SCATTERING (TEMPERATURE, SPECIES CONCENTRATION)
- LASER INDUCED FLUORESCENCE (SPECIES CONCENTRATION)
- LASER TOMOGRAPHY (FLAME FRONT VISUALIZATION)

THEORETICALLY, THE MAJOR PROBLEM IS TO EVALUATE THE FLOW IN THE PRESENCE OF A FLAME, AND TO CALCULATE THE CHEMICAL PRODUCTION TERM.

3. DROPLET COMBUSTION

DROPLET VAPORIZATION AND COMBUSTION ARE THE BASIC MECHANISMS IN SPRAY COMBUSTION

* PHENOMENOLOGY OF SINGLE DROPLET COMBUSTION
* RECENT NUMERICAL PREDICTION RESULTS
* CONVECTIVE DROPLET COMBUSTION
* SPRAY COMBUSTION

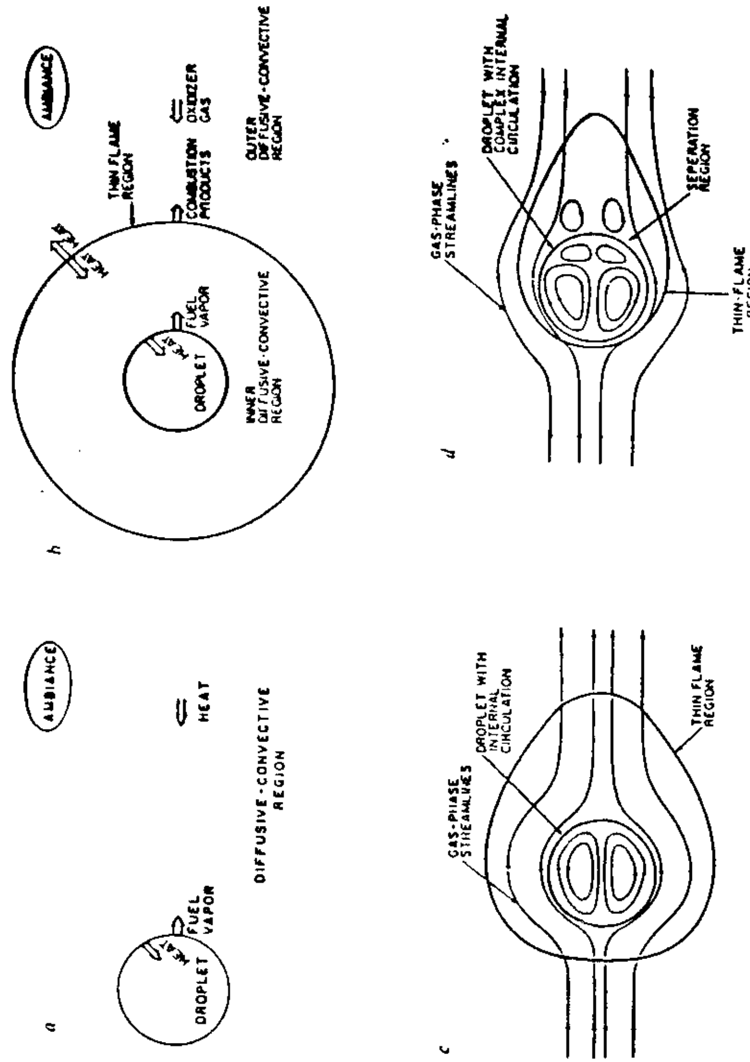
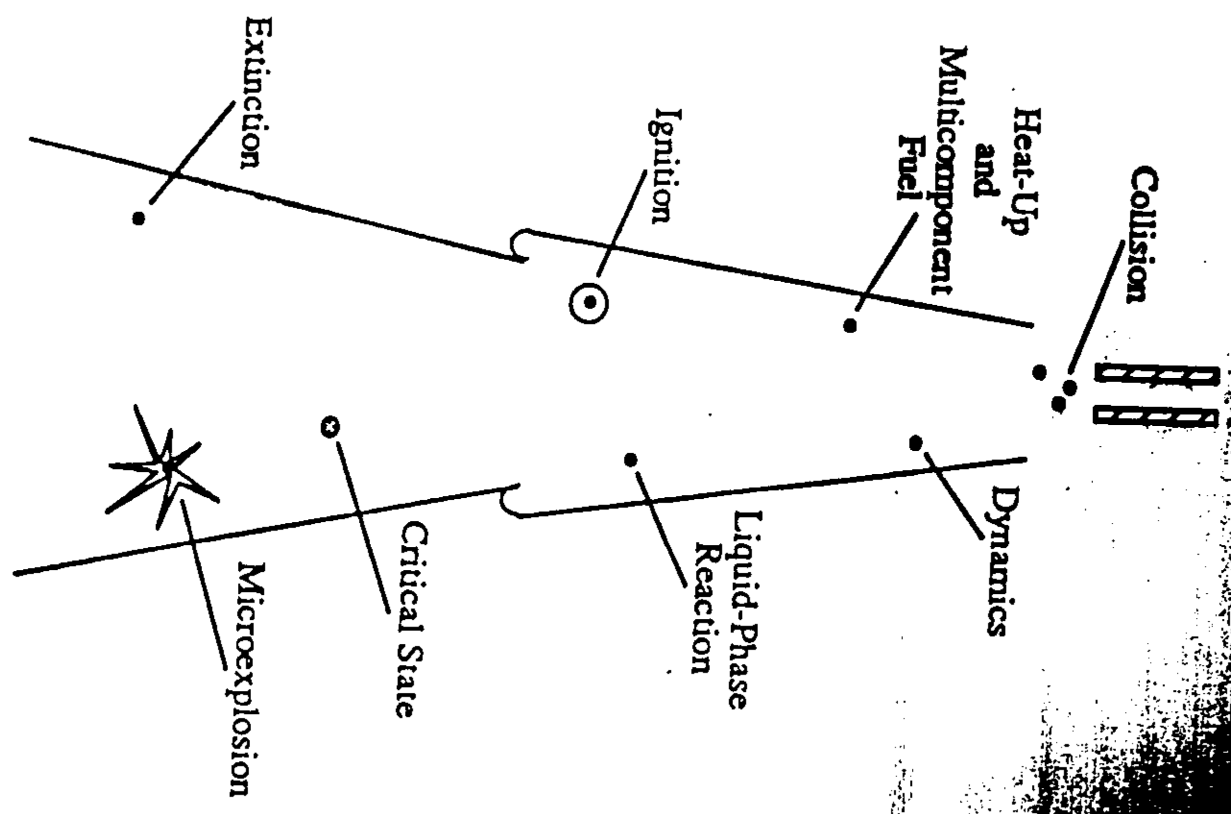


Figure 1



The equations of motion solved in this study are the following:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0 \qquad \text{(Continuity)}$$

$$\frac{\partial}{\partial t}(\rho v_i) + \frac{\partial}{\partial x_j}(\rho v_i v_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right] - \frac{2}{3}\frac{\partial}{\partial x_i}\left(\mu\frac{\partial v_j}{\partial x_j}\right) \qquad \text{(Momentum)}$$

$$\frac{\partial}{\partial t}(\rho C_v T) + \frac{\partial}{\partial x_j}(\rho C_p v_j T) = \frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right) + \Sigma_{n=1}^{N} \Delta h_n \dot{w}_n''' \qquad \text{(Energy)}$$

$$\frac{\partial}{\partial t}(\rho Y_k) + \frac{\partial}{\partial x_j}(\rho v_j Y_k) = \frac{\partial}{\partial x_j}\left(D_k\frac{\partial Y_k}{\partial x_j}\right) + \Sigma_{n=1}^{N} C_{kn} \dot{w}_n''' \qquad \text{(Species)}$$

$$P = \rho \dot{R}(Y_k) T \qquad \text{(Eq. of State)}$$

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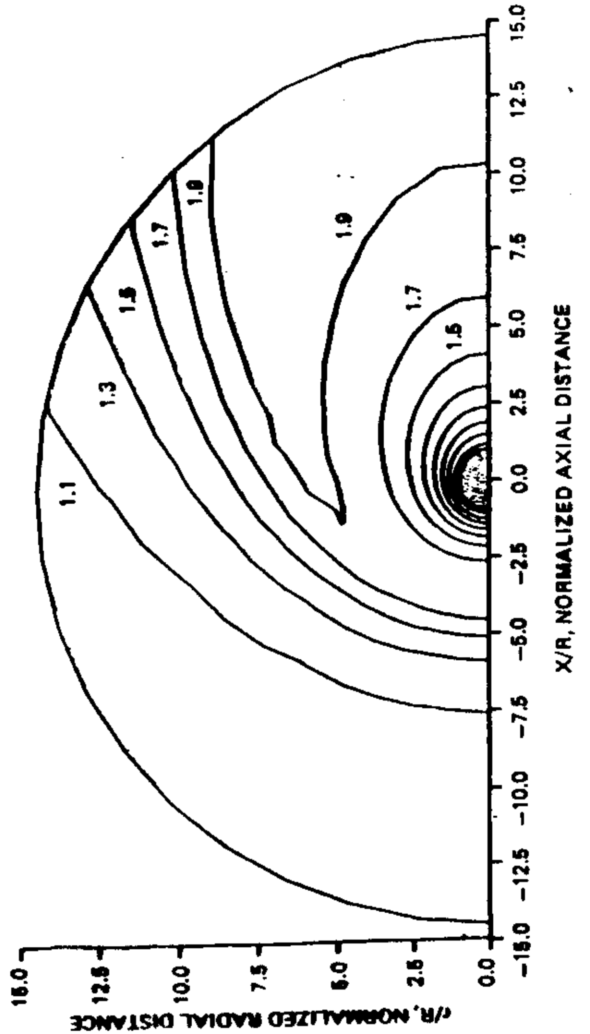

Figure 9. Isotherm pattern for burning droplet. Re=2, Da= Da_{ref}, isotherms are values of T/T_∞.

3.0 Droplet Experiments

- Objectives:

  (a) Discuss advantages and disadvantages of various types of droplet experiments.

  (b) Judicious to match droplet phenomena with droplet experiment for simplicity and controllability.

3.1 Suspended Droplet

Advantages

- Simple
- Stationary
- Ease of Imaging

Disadvantages

- Buoyancy *
- Fiber Interference *
  - large size
  - shape distortion
  - heat-transfer
- Limited to relatively non-volative fuels
- No sampling *

* Can be improved/minimized

3.2 Porous Sphere

Advantages

- Steady
- Ease of intrusive probing of gas-phase structure
- A good simulator of steady-state diffusion flame burning

Disadvantages

- Buoyancy
- Supply tube interference
- No liquid-phase information
- Steady
- Basically not a droplet experiment

3.3 Freely-Falling Droplet (1)

Generators

- Vibrating Orifice
- Chopper Technique
- Piezoceramic Generator
- Aerodynamic Generator

3.3 Freely-Falling Droplet (2)

Advantages

- Monodisperse
- Droplet sampling possible
- Compact (piezoceramic generator)
- Small size (100 - 300 μm)
- Controllable spacing, initial composition, combustion environment
- Low/high Re

Disadvantages

- Finite external convection
- Finite chamber length
- Focusing/resolution limit for droplets smaller than 50 μm

3.4 Levitated Droplet

Advantages

- Stationary for optical diagnostics
- Controllable environment and convection
- Small droplets

Disadvantages

- Controllability of initial state (?)
- Controllability of ignition (?)
- No sampling

3.5 Techniques for Reducing Buoyancy

Need: Most non-convective droplet models assume spherical symmetry, which can be totally destroyed by buoyancy.

Techniques:

(a) Reduce size.
(b) Reduce pressure.
(c) Drop tower:
  Suspended droplet.
  Droplet generator.
(d) Space station.

3.6 Droplet Temperature Measurements

- Use thermocouple as suspension fiber for droplet.
  (a) One thermocouple: center temperature.
  (b) Three thermocouples: center and peripheral temperatures for spherically-symmetric situations.
- Exciplex thermometry

4.0 Suggestions for Experiments

- Objectives:
  (a) To provide data of high degree of fidelity for model simulation.
  (b) To isolate and thereby identify effects of individual processes.
- Spherically-symmetric droplet combustion offers a simple and clean flow configuration for model development and validation, including diffusion flame kinetics.

.1 Standard Droplet Combustion Experiment

Objective: Provide data of spherically-symmetric, single-component droplet combustion without droplet heating, for model validation.

Special Considerations:

(a) Spherical symmetry (no buoyancy).
(b) Low boiling-point fuels (minimum droplet heating): C_6-C_8 alkanes, C_1-C_3 alcohols.
(c) Initial state: anytime after the short initial heating transient; need to specify r_{so} and r_{fo}; $T_o(r)$ and $Y_{io}(r)$ can be calculated (or measured).

Measured Quantities:

(a) Bulk droplet size, flame size and thickness as functions of time.
(b) Spatially-resolved temperature and concentration profiles.

Candidate Experiments:

(a) Zero-G.
(b) Suspended droplet under low pressure.

4.2 Droplet Extinction Experiment - I

- Objective: To provide a more stringent test of the oxidation kinetics, especially the extinction kinetics.
- Special Considerations:
  (a) Same as standard droplet combustion experiment.
  (b) Fuel selected should have reasonably well established kinetics.
- Candidate Experiments:
  Same as standard droplet combustion experiment.

4.3 Droplet Extinction Experiment - II

)bjective: To determine the minimum droplet size to support droplet combustion in realistic combustor enviroment.

pecial Considerations:
(a) Small droplet size.
(b) Hot environment of controllable temperature and oxidizer concentration.
(c) Stagnant and convective extinction.

:andidate Experiment:
Freely-falling droplet in combustion environment.

4.4 Droplet Ignition Experiment

- Objective: To provide a stringent test of the ignition kinetics; To deterimine minimum droplet size for ignition in realistic combustor environment.
- Special Considerations:
  - (a) Initial condition crucial, especially regarding fuel vapor accumulation; may use a frozen droplet.
  - (b) Thermal ignition.
  - (c) Minimum droplet heating.
  - (d) Small droplet size.
  - (e) Stagnant and convective ignition.
- Candidate Experiments:
  - (a) Freely-falling droplets.
  - (b) Levitated droplet (?).

4.5 Droplet Heating Experiment

)bjective: To provide information on the development of the droplet temperature profile for model comparison.

;pecial Considerations:
(a) Initial droplet temperature profile important, may either use frozen droplet or experimentally map out.
(b) May not need combustion.

ndependent Parameters:
(a) Fuel volatility.
(b) Ambient temperature.
(c) May use pressure to increase the extent of heating.

:andidate Experiments:
(a) Suspended droplet at reduced pressure.
(b) Freely-falling droplet.
(c) Levitated droplet.
(d) Zero-G.

4.6 Multicomponent Droplet Experiment

- Time- and Spatially-resolved concentration profile within droplet would be nice, but probably difficult.
- Time-resolved, spatially-averaged concentration history obtained through existing sampling technique for freely-falling droplets can be quite useful.
- Modelling needs:
  - (a) Reliable liquid-phase diffusivity.
  - (b) Description of nonideal mixture.
  - (c) Development of a parameter relating volatility differential, liquid diffusivity, and gasification rate to indicate the gasification mode.
  - (d) Description of fuel blend.

4.7 Droplet Drag Experiment

- Objectives:
  - (a) To assess effects of surface mass flux on the droplet drag.
  - (b) To develop drag coefficient.
- Special Considerations:
  - (a) $1 \leq Re \leq 100$, $0.1 \leq B \leq 10$.
  - (b) Well-defined initial conditions.
  - (c) Minimum droplet heating.
  - (d) No combustion, pure vaporization in hot nitrogen environment.
  - (e) Report both reduced and raw data. For example:

Reduced	Raw
C_D	$(du/dt)(d_s/u^2)$
Re	ud_s
B	$d(d_s^2)/dt$

- Candidate Experiments:
  - (a) Freely-falling droplet.
  - (b) Levitated droplet.

4.8 Droplet Collision Experiment

- Objective: Determine criterion governing droplet coalescence.
- Special Considerations:
  - (a) Vaporization may not be important.
  - (b) May need to work in a thermodynamically-equilibrated fuel vapor environment for proper surface tension.
  - (c) Small droplets (<10μm ?)

4.9 Turbulent Dispersion Experiment

- Objective: Determine influence of turbulence on droplet dispersion.
- Special Considerations:
  - (a) Use well-characterized turbulent flow, possibly even cold flow.
  - (b) Use very volatile droplet to achieve vaporization effect.
  - (c) Vary droplet size and turbulence scales and intensities.

5.0 Current Experimental Research Activities (1)

- Zero-G
  - Avedisian; high p (DOE)
  - Borman; high p (NASA)
  - Gokalp (France/Germany)
  - Niioka/Mitani; high p (Japan)
  - Williams/Dryer (NASA)
- Propellant Droplets
  - Dryer/Williams; boron slurry (AFOSR)
  - Faeth/Turns; boron and carbon slurry (AFAPL)
  - Law; carbon slurry, organic azides (ONR); gun LP (ARO)
- Droplet Dynamics
  - Libby/Williams/Seshadri; droplets in stagnation flame (DOE)
  - Law; droplet collision (NSF)
  - Kennedy; turbu lent dispersion.

[illegible] GRAVITY COMBUSTION

by

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ABSTRACT

The general objectives of reduced gravity combustion research concern the following two issues. First, combustion research in reduced gravity may help to understand and analyze earth-based combustion phenomena by eliminating several complex couplings between buoyant and inertial or viscous forces. In this perspective we may gain insight on, for example, the problem of counter-gradient diffusion in turbulent premixed flames, or more generally, on the role of buoyancy in the balance of the turbulent kinetic energy in turbulent flames. Reduced gravity combustion research may also enlighten the role of buoyancy in the stability of laminar flames.

The second important issue is related to space-based combustion phenomena. For example, flame spread along solid surfaces, which has important consequences on the safety considerations in a spacecraft, is a typical research area within this perspective.

The reduced gravity combustion activities supported by the European Space Agency since 1984 are also following these two objectives. In January 1984, ESA issued a call for experiment proposals to investigate combustion phenomena under microgravity conditions. Following the positive response to this call for proposals, a European Combustion Expert Group was formed and a number of KC-135 parabolic flight experiments have been carried out.

A multiburner combustion chamber (MUCC) has been constructed at the Laboratoire d'Aérothermique of CNRS at Meudon, France (Drs. Prud'homme and Durox). Two experiments on non-reacting turbulent variable density jet flows have been carried out by using this facility. A team from the University of Bochum, FRG (Profs. Leipertz and Kremer) investigated by an infrared camera the structure of heated He-CO2 transitional axisymmetric jets. Another group from Imperial College, London, UK (Dr. Lockwood) investigated the temperature fluctuations in the same jet with fine thermocouples. Both investigations showed the importance of buoyancy on the development and structure of these variable density and moderate Reynolds number jets.

[illegible] of the [illegible] the influence of g[illegible] on the t[illegible] flame surface area and on the fluctuation frequency of the [illegible]

[illegible] of flame spread over [illegible] surfaces [illegible] conducted by two groups. The group [illegible] (Drs. Bryant and Judd) also [illegible] the [illegible] experiments with several materials. [illegible] gravity reduces the overall rate of [illegible] propagation, the flame temperature and the airgap across which burning can propagate. The influence of the absence of gravity on the flame spreading velocities over PMMA samples has been investigated by the group from the Propulsion Laboratory at the University of Madrid, Spain (Profs. Sanchez-Tarifa and Linan) in specially designed combustion chambers. They showed that flame spreading velocities are lower at reduced gravity conditions. They also investigated the influence of gravity with different chamber pressure and oxygen concentration conditions.

Droplet burning experiments have been carried out by the group from CNRS at Orléans, France (Drs. Gökalp and Chauveau) in collaboration with the University of Karlsruhe, FRG (Prof. Leuckel) by using two specially designed droplet burning facilities: a convective droplet burning facility and a high pressure droplet burning facility. Suspended and free-floating single n-heptane droplet burning parameters have been determined by using a rapid video camera. Another facility has also been recently developed at ZARM, University of Bremen (Prof. Rath) and was successfuly tested during parabolic flights.

Finally, Professor F. Weinberg from Imperial College, London, UK, performed experiments on the electric field induced flame convection in the absence of gravity.

For the next phases of the reduced gravity combustion activities, several facilities are available in Europe. Parabolic flights using a Caravelle 234 will be possible in France starting in february 1989. A 110 meter drop tower will be available from 1989 onwards in Bremen. Also, ESA is participating in the German TEXUS and the Swedish MASER Sounding Rocket programmes. A Long Duration Sounding Rocket by means of which up to 15 minutes of microgravity conditions could be achieved is being studied.

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